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SIZE OF SAND GRAIN AND CRITICAL WIND VELOCITY AT WHICH SANDS GRAINS BEGIN TO MOVE (Continued)

M. Akiba

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16. Abstract

The report discusses the equivalent of theoretical and experimental calculations on the effect of sand grain size and wind velocity on the critical wind velocity at which sand grains begin to move. There is good agreement between the theoretical and experimental equations. The velocity of natural wind and the effect of an increase in air density due to increase humidity are also taken into account.

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M. Akiba

I. Introduction /53*

There have been numerous studies since the ancient times on the subject of blown sand in connection with erosion control. However, the observations are so varied and inconsistent that they do not clarify the relationship between sand grain size and the critical wind velocity at which the sand grains begin to move. Having studied sandy terrains from the standpoint of land use, the writer became aware of the existence of a relatively consistent correlation between the two factors mentioned above, and proceeded to publish theoretical definitions of this relationship [1]. For various reasons, experimental facilities had not been available until the present time, so that it had not been possible to determine to what extent these abstract theoretical equations corresponded with experimental results. What follows is a brief description concerning this comparison which we were finally able to carry out although in approximate terms.

II. Theoretical Equations

Since the writer has already published the theoretical equations, only a summary will be given on this occasion.

The force (F) required for causing a sand grain to move is given by

$$F=\frac{4}{3}\mu\rho\pi r^3 w \qquad (1)$$

* Numbers in the margin indicate pagination in the foreign text.

where μ is the coefficient of friction of the sand grain; ρ is the specific gravity of the sand grain; π is the ratio of circumference to diameter; r is the radius of a sand grain considered as a sphere; and w is the weight of a unit volume of water. But, since the resistance would vary in actuality according to the conditions of the fixation and arrangement of the grain, it would be more reasonable to consider (μ_0), instead of (μ). Letting k be the coefficient for the condition of the arrangement, we get

$$\left.\begin{array}{l} \mu_0 = \mu(1+k) \\ \mu_0 = k'\mu \end{array}\right\} \tag{2}$$

and consequently,

$$F = \frac{4}{3} k' \pi w \mu \rho \gamma^3 \tag{3}$$

As for the magnitude of the force (F_W) caused by the wind velocity (W), it would vary depending not only on the magnitude of the wind, but also on the size and form of the object directly facing the wind direction, and temperature and humidity, among other things, but nevertheless /54

$$F_W = C_w \pi r^2 \frac{\gamma}{2g} W^2 \tag{4}$$

where C_W is the drag coefficient of the object with respect to the wind, which varies according to wind velocity and form of the object. Here it is assumed nevertheless to be practically a constant; and γ is the weight of a unit volume of air (including humidity). Therefore, since the sand grain finally begins its motion when F = F_W is reached, we get

$$W = \sqrt{\frac{8 g w k'}{3 C_w \gamma}} \sqrt{\mu \rho r} \tag{5}$$

$$W = C\sqrt{\mu \rho r} \tag{6}$$

from (3) and (4). For a sand grain of the same system with (d) as its diameter, we get

$$\left.\begin{array}{l} W=C'r^{0.5} \\ W=C''d^{0.5} \end{array}\right\} \quad (7)$$

In other words, the correlation between the sand grain and the wind velocity is as expressed by equation (7), which would mean that the wind velocity is proportional to the square root of either the radius or the diameter of the sand grain.

III. Experimental Equations

1. Experimental Method

Wind velocity: This was measured in terms of artificial wind for which a Micox blower was used. The wind velocity magnitude ranged from 3.0 to 15.0 m/sec. It was expressed in terms of the mean wind velocity (W) at the height of about 5 mm from the surface of the sand.

The sand surface was obtained by sifting Tamagawa River gravel with Tyler's standard sieves. Using 12 sieves, five to six kinds of grains were selected from sieves of adjacent mesh diameter sizes. The mesh sizes of the sieves and the grain sizes samples are as follows

Mesh count (per inch)	6	7	9	10	14	16	28	32	50	60	115	150
Mesh size (mm)	3.327	2.794	1.981	1.651	1.163	0.991	0.589	0.495	0.285	0.246	0.124	0.104
Mean diameter (mm)	3.06		1.816		1.077		0.542		0.265		0.114	

The specific gravity of the sand ranged from 2.55 to 2.8.

Containers: Container No. 1 consisted of a glass plate on which grains which were of the same size as the sand grains being tested were made to adhere with paraffin. On top of these grains, the sand samples were placed in a layer several millimeters thick.

Container No. 2 consisted of a brass ring 3 mm in height and 3 cm in diameter, which was filled with sand in such a way that the sand was exposed by an appropriate amount over the rim of the ring.

Container No. 3 consisted simply of a glass plate on which an extremely thin layer of sand was arranged in as close an approximation of a single file as possible.

When sand is placed in the containers and the wind is applied, there are grains which are blown off initially in an irregular manner. Taking this phenomenon into account, the wind velocity was raised to a fairly high level once to set the superficial grains in scattering motion. The wind velocity was then lowered to allow the sand to approach a settled state against the wind, after which the velocity was increased gradually until the grains started to fly off. The "critical wind velocity at which sand grains begin to move" was defined as the critical wind velocity at which the above phenomenon became continuous in our observation. The experiment was carried out by several individuals who were asked to follow this method. It became evident that the recognized margin of error was relatively small, ranging from 1-7%. /55

2. Experimental Results

The results of the experiments and the experimental equations are organized as shown below. The critical wind velocities are mean values of several trials in each case.

Container No. 1 with sand resting on grains of the same size: The mean critical wind velocity values (W) (m/sec) recorded in experiments conducted in mid-summer months of July and August, late autumn months of October and November, and the severe winter months of January were as follows.

Sand grain (m. m.) / No.	0.114	0.265	0.542	1.077	2.15	3.06	Remarks: Month of experiment	Remarks: Experimentors
1	3.7	5.1	7.6	9.7	12.75	15.05	Av./late July	Av./Mssrs. Kira/Toyoda
2	3.5	4.9	6.95	10.1	12.8	15.0	Av./early Aug.	Writer
Values calculated from equation 8	3.56	5.19	7.18	9.65	13.06	15.27		
3	3.4	4.7	5.93	8.43	—	10.9	Av./late Oct.	Mr. Furuhata
Values calculated from equation 8	3.29	4.65	6.17	8.17	—	12.4		
4	2.9	3.9	5.55	7.7	10.1	—	Av./late Nov.	
5	2.87	3.83	5.35	7.93	10.2	11.1	Av./late Nov.	Writer and
Values calculated from equation 8	2.72	3.94	5.42	7.3	9.93	12.33	Av./mid Jan.	Mr. Furuhata
6	2.8	4.15	5.47	8.07	—	11.0		
Values calculated from equation 8	2.8	4.07	5.62	7.5	—	11.6		Mr. Furuhata

The following equations are formulated by plotting the experimental results shown above.

$$
\left.
\begin{array}{ll}
\left.\begin{array}{l}\text{No. 1}\\ \text{No. 2}\end{array}\right\} & [W]=9.33\,d^{0.44}\\
\text{No. 3} & [W]=7.95\,d^{0.44}\\
\left.\begin{array}{l}\text{No. 4}\\ \text{No. 5}\end{array}\right\} & [W]=7.08\,d^{0.44}\\
\text{No. 6} & [W]=7.25\,d^{0.44}
\end{array}
\right\} \qquad (8)
$$

Container No. 2 with sand filling a frame: The experimental results and the experimental equations in this case are as given below. When the experimental equations are compared with the experimental results, it is seen that there is a fairly good agreement with the exception of the maximum error of 20% for No. 3.

Sand grain (m. m.) / No.	0.114	0.265	0.542	1.077	3.06	Month of Experiment	Experimental equation ...9
1	3.1	4.4	6.4	8.5	—	Av./late July	$[W]=7.83\,d^{0.47}$
2	3.1	4.2	5.8	8.8	13.0	Av./early August	
3	3.69	4.35	5.83	7.86	10.44	Av./late October	$[W]=7.59\,d^{0.42}$
4	2.45	3.53	5.01	7.32	10.35	Av./late November	$[W]=6.45\,d^{0.445}$

Container No. 3 with sand arranged on glass plate: In this case, the sand begins to be blow off at extremely low wind velocities.

Sand grain (m.m.) / No.	0.114	0.265	0.542	1.077	3.06	Month of experiment	Experimental equation ...10
1	1.8	2.2	3.0	3.6	4.8	Av./late July	With respect to mean values
2	2.8	3.6	4.25	5.1	6.25	Av./early August	$[W]=4.26\ d^{0.29}$
3	2.77	3.4	3.9	4.6	—	Av./late October	$[W]=4.58\ d^{0.25}$

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IV. Discussion

The differences between the experimental equations (8), (9), and (10)[1] are assumed to have been caused by various effects which are due to the differences between the containers, but what are the deviations from the theoretical equations which led to these differences?

(1) In the case of the above-mentioned equations (8) and (9), the difference is believed to be limited to the difference in the coefficient "C", so that their indices are assumed to be about the same. It is reasonable to assume that since the sand grains are resting on other grains in both cases, they are under practically the same conditions as far the projected area of the wind force and the frictional resistance are concerned. The presence or absence of the annular frame causes a difference in C_W with respect to the wind, so that the presence of the annular frame increases this drag coefficient to thereby make the wind velocity smaller. In other words, it may be assumed that the negative pressure drag is increased by the use of the annular frame, so that in the case of this experiment, it was possible to cause the sand to blow off with wind velocities which were about 10% lower compared to the case without the annular frame.

(2) As far as the causes of the difference between equations (7) and (8), on the one hand, and equation (10), on the other, are concerned, one should first list the fact that while the

[1] [Translator's note: Equations (9) and (10) not included in original Japanese document.]

former equations are chiefly determined by the resistance of the cohesive force and by the friction among the grains, the latter is determined by the adhesive resistance and by the friction between the grains and the glass plate. As the second cause of the difference, one should cite the fact that a difference in the projected area of the wind force occurs between the former and the latter. It is already generally known that the size of the grains affects the resistance and the adhesive force [2]. According to J. Schachbarian's experiment, the adhesive force increases with the reduction in grain size, while the coefficient of friction increases with the reduction in grain size when moisture is present, but an inverse tendency is observed when the grains are dry. In order to investigate the kind of effect the grain size has on the frictional adhesion between the glass plate and the sand grains, the writer dispersed almost a single layer of sand grains on a glass plate, secured one end of the glass plate and gradually lifted the other end. The angle (θ) formed by the glass plate and the horizontal plate in the instance the majority of the grains fell was measured with a clinometer, and the coefficient of adhesive friction was assumed to be given by $\tan \theta = \mu$. The result of this experiment showed that the value of (μ) was approximately three times greater in summer with its high humidity than in autumn when the humidity is low.

Grain (m.m.) / No.	0.114	0.265	0.542	1.077	3.06	Month of experiment
1	1.08	0.86	0.76	0.57	0.41	Av./July and August
2	0.775	0.53	0.44	0.36	0.30	Av./October

Due to the divergence of almost 10% which was observed just during summer depending on the climatic conditions, experimental procedure, and so on, it was decided to adopt a considerable number of mean values. Some of these are given above. /57

When these values are plotted approximately, the following experimental equations are obtained.

$$\left.\begin{array}{ll} \text{No. 1} & \mu = 0.596\, d^{-0.305} \\ \text{No. 2} & \mu = 0.373\, d^{-0.300} \end{array}\right\} \qquad (11)$$

Judging from the above table or from equation (11), it is evident that when the humidity is fairly high, the grain size has an effect on the force of adhesive friction with respect to glass. However, since metoerological and climatic conditions vary from time to time, equation (11) would also vary from time to time.

By substituting equation (11) for (μ) in equations (5) or (7), we get

$$\begin{aligned} W &= C''' \mu^{0.5} d^{0.5} \\ &= C_1 d^{(-0.3)0.5}\, d^{0.5} \\ &= C_1 d^{-0.15}\, d^{0.5} \end{aligned}$$

that is

$$W = C_1\, d^{0.35} \qquad (12)$$

It is seen that equation (12) comes quite close to equation (10).

(3) As far as the difference between the theoretical equation (7), which was formulated from an abstract concept, and the experimental equation (8) is concerned, it is almost negligible since the two are so close, but let us nevertheless examine it as a matter of routine procedure.

Since the theoretical formula for equation (7) concerns an ideal grain, it is entirely conceivable, as already stated in equation (2), that the projected section of the wind force as well as the drag coefficient against the wind force would vary according to the arrangement of the grains. It is also conceivable that the grain size, along with the wind velocity, has a certain amount of effect on the drag coefficient (C_w). It should be noted at this point that for the sake of simplicity, (C_w) was assumed to be a constant. In addition, one must also take into consideration the effect the grain size would sometimes have on the force of frictional cohesion. Also, the wind velocity in the experiments was somewhat different in nature from the wind velocity adopted for the theoretical equation. In other words, while the critical wind velocity in the theoretical equation is considered to collide directly with the sand grains, the experiment used the mean wind velocity at a certain distance above the sand surface.

Generally speaking, therefore, we get

$$W = C_1''' d^{0.5-m} \tag{13}$$

where

$$m = m_1 + m_2 + m_3 \tag{14}$$

(4) It is known that m takes a smaller value compared to the experiment. m_1 is not the ideal grain form and, in addition, it is a value related to the wind force drag (C_w) resulting from the grain size variation itself. In other words, width and depth are manifested with considerable clarity because it is not an ideal grain, and, as a result, a slight variation from the ideal grain occurs in the drag and the projected area with respect to the width, and in the drag in the direction of the flow with respect to the depth. In general, when the frictional drag of the wind force is the main component, it is expressed as

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$$C_w = \varphi\left(\frac{Wl}{\nu}\right) \tag{15}$$

where W is the wind velocity; l is the length or width; and ν is the coefficient of kinetic viscosity. In other words, it is considered to be a function of the Reynold's number.

On the other hand, if the form drag of the wind force is the main component, it is expressed for most substances of similar forms as

$$C_w \fallingdotseq \text{Constant}. \tag{16}$$

A considerable amount of research has been conducted regarding the above-mentioned items with respect to objects in the air, if not on the ground. Such studies include descriptions of the functional relation of equation (15) for the case of an object placed parallel to the direction of the flow [3], or the drag coefficients and curves for a variety of forms [4]. Since there is a risk in adopting the relation of equation (15) unconditionally for substitution without investigating the relationship between sand and wind, which is to say the conditions of the wind velocity and the grains on the ground rather than in the air, we will forego its discussion in this report and will wait for the results of further research. However, it would seem that the relation between the mean wind velocity (W) within a certain distance from a wall and the wind velocity W which collides directly with the sand grains may be assumed to be not far off from

$$[W] = C_0 W \tag{17}$$

within the range of the wind velocity adopted for the present experiment. This was deduced from the results of a simple study of the vertical velocity distribution using a micro pressure

pressure gauge devised by the writer. Moreover, a similar assertion has been made concerning the motion of a particle in water [5]. But, judging from the results of the experiment, even if a function of the grain is contained in the drag coefficient when (W) is being used, it would not be of a magnitude that would cause a problem, with m_1 being a considerably small entity.

(5) m_2 signifies the effect of the grain on the force of frictional cohesion, and it is again a very small value. In order to investigate this, the writer placed sand in a glass box measuring 25 cm in height, 15 cm in length, and 5 cm in width, and then measured the slope of the sand after propping up the box with a plank and suddenly releasing it. The result was that the incline was the mildest at the lowermost part and the steepest at the uppermost part in the angle of repose exhibited. Since some of the sand spilled out from the lower end of the glass box, the angle (θ) formed by the incline one-third of the way and the horizontal plane was measured for the various grain sizes. Assuming that $\tan\theta = \mu$, the results were summarized and tabulated below.

Grain size (m.m.) / No.	0.114	0.542	1.077	3.06	Season of experiment
1	0.685	0.614	0.610	0.565	Av./summer
2	0.665	0.598	0.663	0.552	Av./ autumn
Grain size, sieve mesh number / No.	60~115	50~32	32~28	28-16	
3	0.630	0.637	0.641	0.630	Av./winter

As it is seen in the above table, hardly any effect due to the grain size is observed. No. 3 obviously lacks consistency with respect to the grain size, but it was included for reference. It is almost possible to ignore the effect of the grain size throughout. If an equation is nonetheless sought for No. 1, we get /59

$$\begin{aligned} \mu &= 0.75\, d^{-0.05} \\ m_2 &\doteqdot -(0 \sim 0.025) \end{aligned} \tag{18}$$

Therefore, $m_2 \doteqdot (0-0.025)$. By taking this into consideration, the experimental equation becomes even closer to the theoretical equation.

(6) m_3 can be considered as something which occurs as the result of the variations in the wind velocity in its ground distribution and along the critical layer, in the grain arrangement and the grain form, and in the degree of the settlement of the sand according to the grain size as they affect the projected area. It is however known that in the present experiment, we get approximately

$$[W] = (7 \sim 9)\, d^{0.41 \sim 0.45} \tag{19}$$

(7) In order to compare the theoretical equation (5) and the experimental equation(19), the suitability is tested by applying figures which approach the actual situation. From equations (5) and (17), we get

$$[W] = C_0 \sqrt{\frac{1}{2}\,\frac{4}{3}\,\frac{2g}{\gamma}\,\frac{w}{C_w}\mu\, k' \rho} \quad d^{0.5-m}$$

Appropriate figures are selected for the coefficients in the following manner. Expressing in terms of d = 1/1000 m, that is, mm, and using

$$\frac{\gamma}{2g} = \frac{1}{16}, \quad C_w = 0.2 \sim 0.6 = 0.4 \quad w = 1000$$
$$\rho = 2.5 \sim 2.8 = 2.7 \quad \mu = 0.6 \quad k' = (1+k) = 1.6$$

we get

$$\sqrt{\frac{1}{2}\,\frac{4}{3}\,\frac{2g}{\gamma}\,\frac{w}{C_w}\mu k'\rho}=\sqrt{\frac{1}{2}\,\frac{4}{3}\times 16\frac{1}{1000}\times 0.6\times 1.6\times 2.7\frac{1}{1000}}\doteqdot 8.3$$

$$[W]=8.3C_0\,d^{0.5-m} \tag{20}$$

Assuming that C_0 is approximately 1, about the same value as the experimental equation is obtained, thus indicating experimentally that the theoretical equation is more or less correct.

V. Conclusion

From the material discussed so far, it became apparent that the theoretical equations were more or less correct, and that the experimental equations were equivalent to slight adjustments of the former. The reasons for this adjustment are, among other things, the fact that the form and the arrangement of the grains are not those of an ideal sphere, the fact that the wind velocity used for the critical wind velocity did not collide directly /60
with the grains but it was the mean value up to a certain height above the sand, as well as the fact that the force of friction also varies according to grain size.

Since in reality, too, the velocity of natural wind is represented by the velocity at a certain height above the ground, it is necessary to await the results of further research into its ground distribution as well as into the various forms and arrangements of the aforementioned grains.

An increase in air density would be accompanied by an increase in air resistance unless the increase in the density was caused by the presence of humidity. In the latter case, the sand grains would gain in the force of frictional adhesion by absorbing this moisture. This is one of the reasons for the fact that the blown sand phenomenon is less likely to occur in the summer than in the winter.

In substance, the relation between sand grains and the critical wind velocity is more or less correctly explained by the theory published by the writer several years ago, that is, the following is valid

$$[W] = C_0 \times C'' d^{0.5-m}$$

$$m = 0.05 \text{ 内外}$$

$$C'' = 7 \sim 9 \qquad C_0$$

$\fallingdotseq$ 1 (varies according to wind direction)

The fact that it is adequate to use mean values for the wind force drag coefficient, the adhesive friction coefficient, etc. during the above procedures is evident from the comparison with the experimental values.

The above conclusion should be applied within the range in which sand grains can undergo motion as a single granular body, that is, from fine sand about 0.1 mm to coarse sand. Grains finer than these can hardly act as single granular bodies due to such factors as wind force drag and the force of adhesive friction, while larger grains, such as gravel, would also be out of the range of application of such factors as the grain form, arrangement, the degree of settlement, etc. would vary so widely that their conditions with respect to the wind force would be altered in nature.

In closing, I would like to express my deepest gratitude to Mr. Tanaka and others to whom I am greatly indebted for their assistance.

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